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VERY LARGE TELESCOPE SPECTRA OF CARBON STARS IN THE LARGE MAGELLANIC CLOUD AND THEIR METALLICITY DEPENDENCE[1]

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ABSTRACT

Very Large Telescope (VLT) *L*-band spectra of six carbon stars in the Large Magellanic Cloud are presented. The stars show absorption bands at 3.1 μm (HCN and C_2H_2), and 3.8 μm, which is probably due to C_2H_2. Two LMC stars show strong 3.5 μm HCN absorption. The equivalent widths of the 3.1 μm and 3.8 μm bands are systematically larger in LMC carbon stars than in carbon stars in the solar neighborhood. Moreover, the ratio of the equivalent widths of the 3.8 and 3.1 μm bands is much larger in the LMC, suggesting a higher ratio of $n(C_2H_2)/n(\mathrm{HCN})$. The stronger absorption bands are in contrast to the assumption that if the elemental abundances are scaled from the carbon star's abundances in the solar neighbor, the abundances of these molecules are less at lower metallicity. We argue for a systematically larger C/O ratio in LMC carbon stars. In the Galactic carbon stars $n(\mathrm{C})/n(\mathrm{O}) \approx 1.05$–1.1 on average; our chemical model shows that the stronger molecular bands in the LMC carbon stars could be explained with $n(\mathrm{C})/n(\mathrm{O}) > 1.2$. The higher C/O ratio can also explain the higher ratio of $n(C_2H_2)/n(\mathrm{HCN})$ in LMC stars than in the solar neighborhood.

Subject headings: infrared: stars — Magellanic Clouds — stars: abundances — stars: AGB and post-AGB — stars: atmospheres — stars: carbon

1. INTRODUCTION

Carbon atoms are synthesized in asymptotic giant branch (AGB) stars via helium burning. During the third dredge-up the newly synthesized atoms are carried from the bottom to the surface of the convective envelope. At low metallicity, evolution models of AGB stars with an initial mass of 2.0–2.5 $M_\odot$ predict that carbon is enriched efficiently in the atmosphere, with the number of oxygen atoms remaining approximately constant (e.g., Vassiliadis & Wood 1993) (but not completely constant; Péquignot et al. 2000). For the most massive AGB stars, nitrogen may also be enhanced due to the onset of hot bottom burning, converting the new carbon into nitrogen via the CNO cycle (e.g., Marigo & Girardi 2001).

This suggests that the elemental abundances at different metallicities are not simply scaled from the solar abundance. The effect can be studied in the Large Magellanic Cloud (LMC), where the metallicity is about a factor of 2 less than in the solar neighborhood. In the atmospheres of AGB stars in the LMC, carbon, and possibly nitrogen as well, is generally expected to be more abundant relative to oxygen. The ratio of carbon-rich stars with respect to oxygen-rich stars is indeed higher in the LMC than in the solar neighborhood. There is also tentative observational evidence for enhanced molecular abundances: Lançon & Wood (2000) suggested that two "oxygen-rich" LMC supergiants show relatively stronger CN absorption bands than galactic supergiants.

To investigate the metallicity dependence of the atmospheres of AGB stars, we obtained infrared spectra of carbon stars in the LMC. We find that the equivalent widths of molecular bands are systematically larger in LMC carbon stars than in Galactic carbon stars. The observed spectra and chemical models indicate that the abundance of especially C_2H_2 is enhanced.

2. OBSERVATIONS

Spectra in *L*-band of six carbon stars in the LMC were obtained with the Infrared Spectrometer And Array Camera (ISAAC) at the Very Large Telescope (VLT) of ESO Paranal, Chile, on 2001 December 12–14. The sky condition was photometric on December 13 and partly cloudy on December 12 and 14. The sample is selected from Trams et al. (1999a) and van Loon, Zijlstra, & Groenewegen (1999).

The wavelength resolution of the ISAAC observations was $\lambda/\Delta\lambda \sim 600$. As telluric standards, B dwarfs and giants from the *Hipparcos* catalog were observed after every target observation. The spectrum of the telluric standard is assumed to be a blackbody of the effective temperature based on the spectral type from the *Hipparcos* catalog. The data were reduced using the Eclipse package and IDL. An exposure of the twilight sky was used for flat-fielding. The wavelength calibration is based on exposures of an Ar + Xe arc lamp with the same wavelength setting as the target observations. The flux error is estimated from ten nearby sky pixels in the image.

Representative spectra of LMC carbon stars are shown in Figure 1. Several molecular bands are seen:

1. C_2H_2 and HCN bands at 3.1 μm;
2. HCN band at 3.5 μm;
3. a band at 3.8 μm, tentatively identified as C_2H_2.

In Figure 2 a spectrum of an LMC carbon star, IRAS 04496−6958, is compared with that of a Galactic carbon star, V Cyg, with similar $K-L$ color. All of the 3.1, 3.5, and 3.8 μm bands are deeper in IRAS 04496−6958 than in V Cyg.

[1] Based on observations obtained at the European Southern Observatory, Chile (proposal 68.D-0660).

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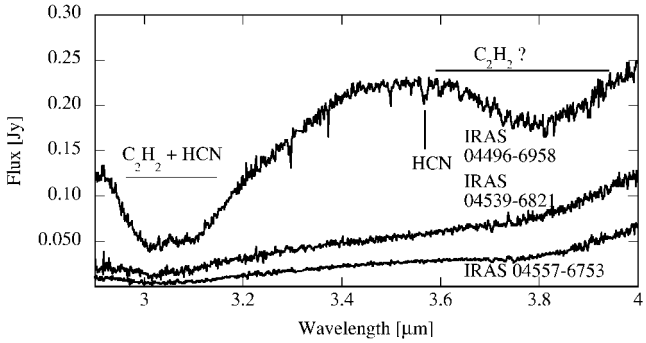

FIG. 1.—Example of LMC carbon star spectra. In IRAS 04496−6958 the HCN and C_2H_2 band at 3.1 μm, the HCN 3.5 μm band, and the 3.8 μm band are seen. Atmospheric lines remain, especially around 2.9 and 3.3 μm.

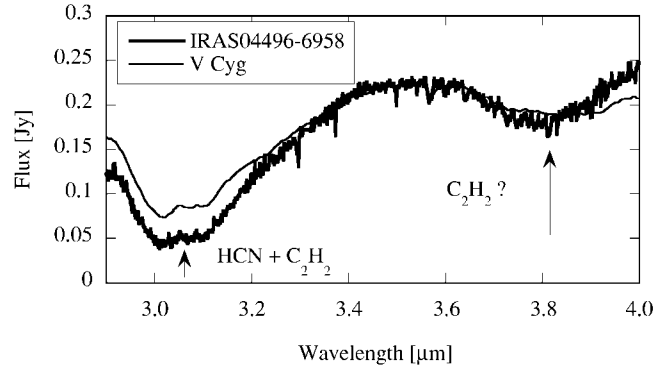

FIG. 2.—Comparison of the LMC star IRAS 04496−6958 and the Galactic star V Cyg, whose $K-L$ colors are similar. There are differences in the depth of the molecular features at 3.1 and 3.8 μm. Due to the different wavelength resolution, small features in IRAS 04496−6958 are more prominent.

We discuss the difference in equivalent widths of these molecular bands between the LMC and Galactic carbon stars in the following sections.

The identification of the 3.8 μm absorption band as C_2H_2 was made by Goebel et al. (1981), using a KAO spectrum of the carbon star V CrB. The 3.8 μm feature in the *ISO*/SWS spectra of the Galactic carbon star R Scl is also identified as C_2H_2 by Hron et al. (1998). The feature in V Cyg is similar. However, the shape of the feature in the LMC carbon star IRAS 04496−6958 looks slightly different. The deepest wavelength is 3.8 μm in IRAS 04496−6958, while it is 3.9 μm in R Scl and V Cyg. A difference in excitation temperature or column density could produce such a wavelength shift, but there is no proof for this. The identification of the 3.8 μm feature in LMC carbon stars as C_2H_2 is therefore tentative but will be assumed in the discussion below.

3. EQUIVALENT WIDTHS OF THE MOLECULAR BANDS

Figure 2 suggests that the molecular bands are stronger in LMC carbon stars than in Galactic carbon stars. The equivalent widths (W) of these three major bands are measured as summarized in Table 1. The results are shown in Table 2. The errors on the equivalent width are estimated from the flux errors.

The equivalent widths of the 3.1 μm band are plotted against $K-L$ in Figure 3. The K- and L-band magnitudes of the LMC carbon stars are taken from Trams et al. (1999a), except for LI-LMC 1813, which is taken from J. Th. van Loon et al. (2002, in preparation). The equivalent width of the 3.1 μm band and $K-L$ colors for additional carbon stars are taken from Groenewegen, de Jong, & Geballe (1994) (Galactic) and van Loon et al. (1999) (LMC, some objects are in common with our sample). van Loon et al. (1999) used 2.9 and 3.3 μm as the continuum level. Some ISAAC spectra are slightly affected by terrestrial atmospheric lines at 3.3 μm, and we use 3.35–3.40 μm instead. On average, this change affects the equivalent width by less than 0.002 μm, but some are affected by up to 0.02 μm.

Additional reference spectra of Galactic carbon stars are taken from the *ISO*/SWS data archive. These were studied by Yamamura et al. (1997), Aoki, Tsuji, & Ohnaka (1998), and Loidl et al. (1999a, 1999b). The K- and L-band magnitudes of these stars are taken from Le Bertre (1992) and Gezari, Schmitz, & Jaylee (1993). Within these samples, stars with colors $1 < K-L < 3$ mag are not sampled. We therefore included stars with this color range from Noguchi et al. (1981) and obtained SWS data from the *ISO* archive.

Table 2 shows that the equivalent widths of the 3.8 μm band in the LMC carbon stars are larger than those in Galactic carbon stars. In *ISO*/SWS spectra published by Yamamura et al. (1997), Aoki et al. (1998), and Loidl et al. (1999a, 1999b), there are only four stars that show the 3.8 μm feature: R Scl, V Cyg, RU Vir, and T Dra. In contrast, all the LMC carbon stars exhibit the 3.8 μm feature. Assuming the 3.8 μm band is due to C_2H_2, Table 2 thus shows a large column density of C_2H_2 in LMC carbon stars—assuming that the excitation temperature is the same.

Figure 2 also shows a tendency for a systematically stronger 3.1 μm band in LMC carbon stars with respect to Galactic stars with the same color. This is consistent with van Loon et al. (1999), who found 3.1 μm band in LMC carbon stars is at least as strong as the one in Galactic stars. Two molecular species contribute to the 3.1 μm absorption: HCN and C_2H_2. Aoki et al. (1998) estimated that in the star WZ Cas, HCN is the dominant source of opacity in this band, with C_2H_2 contributing only up to 10%. The strong 3.8 μm band suggests that this ratio may be different for the LMC stars. This is illustrated in Figure 4, where the equivalent widths of the 3.1 and 3.8 μm bands are plotted against each other. With only a single exception, the LMC stars fall above the Galactic stars. WZ Cas, with its negligible C_2H_2 content, is located in the bottom right corner. This figure suggests that the fractional C_2H_2 contribution to the 3.1 μm feature can be systematically larger in the LMC carbon stars.

It is not clear that C_2H_2 is the sole cause for the larger 3.1 μm equivalent width evident in Figure 3. The error on $W_{3.5}$, a measure of the HCN band, is similar to the strength of the feature in Galactic stars. The data still allow for the possibility of a somewhat higher HCN abundance, which could contribute to the stronger 3.1 μm feature. But the values for $W_{3.5}$ are mostly

TABLE 1
THE DEFINITION OF EQUIVALENT WIDTH (W) FOR THE MOLECULAR ABSORPTION BANDS

Name	Molecules	Measured Region (μm)	Continuum (μm)
$W_{3.1}$	HCN, C_2H_2	2.95–3.35	2.90–2.95, 3.35–3.40
$W_{3.5}$	HCN	3.56–3.58	3.51–3.56, 3.58–3.63
$W_{3.8}$	C_2H_2	3.60–4.00	3.50–3.60, 4.00–4.10

NOTE.—The continuum level is linearly interpolated from the wavelength region in the last column.

TABLE 2
THE EQUIVALENT WIDTHS OF THE SAMPLE

Name	$W_{3.1}$ ($\times 10^2$ μm)	$W_{3.8}$ ($\times 10^2$ μm)	$W_{3.5}$ ($\times 10^2$ μm)	$K-L$
LMC:				
I 04286−6937	7.27 ± 0.23	6.67 ± 0.03	(1.2 ± 6.3)	2.15
I 04496−6958	15.41 ± 0.02	6.07 ± 0.02	7.8 ± 1.8	1.80
I 04539−6821	8.20 ± 0.10	4.60 ± 0.02	(1.8 ± 3.2)	3.00
I 04557−6753	13.92 ± 0.07	6.67 ± 0.02	(0.5 ± 3.4)	2.85
I 05112−6755	9.70 ± 0.14	2.03 ± 0.04	(5.9 ± 5.5)	3.20
LI 1813	11.39 ± 5.29	5.24 ± 0.04	15.5 ± 9.4	3.72
Galactic:				
LP And	4.36	(−0.46)	3.8	2.18
V Aql	10.50	(0.48)	(1.1)	0.79
WZ Cas	14.69	(−0.37)	9.9	0.33
V Cyg	12.62	3.44	10.0	1.18
T Dra	11.29	3.78	11.7	1.59
CW Leo	2.30	(−0.33)	1.1	4.33
TX Psc	7.67	(0.87)	2.3	0.32
R Scl	16.91	2.09	6.9	0.81
S Sct	11.47	(2.06)	4.2	0.43
RU Vir	7.60	1.50	6.9	1.00
GL 2392	7.63	(0.34)	7.3	1.99

NOTES.—Because of the large error in the spectra at 2.9 μm, which is used as continuum, the error of $W_{3.1}$ is larger than that of $W_{3.8}$. In the first column, "I" is *IRAS*, "LI" is LI-LMC, and "GL" is AFGL. Parentheses show nondetection.

upper limits, and a lower median HCN abundance in the LMC can also not be excluded.

In Table 2, a large $W_{3.5}$ is found in two LMC carbon stars, LI-LMC 1813 and IRAS 04496−6958. LI-LMC 1813 will be discussed separately by J. Th. van Loon et al. (2002, in preparation). A high value is found for IRAS 04496−6958, a possible silicate carbon star (Trams et al. 1999b), which would be a good candidate for hot bottom burning.

All equivalent widths show a decrease with redder $K-L$. This is probably due to filling of the molecular absorption bands with continuum dust emission. For stars with $K-L$ larger than unity this color is a measure of dust excess (absorption and emission), rather than the effective temperature of the star, and is related to the dust mass-loss rate. Although the same $K-L$ relates to similar dust mass-loss rates for both LMC and Galactic carbon stars, the correlation with the gas mass-loss rate will be affected by the different gas-to-dust ratio (van Loon 2000).

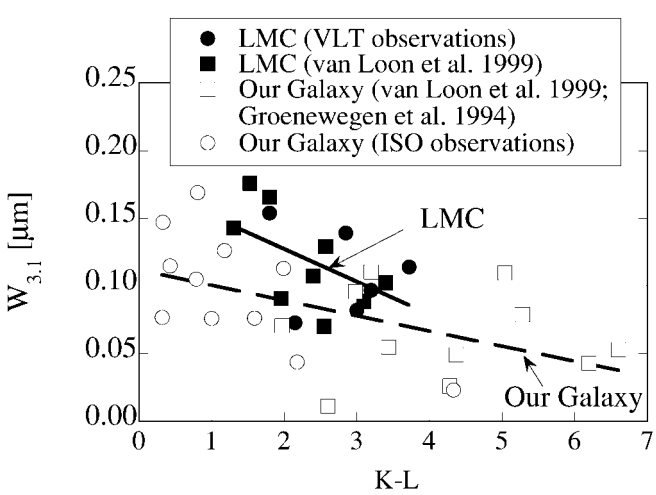

FIG. 3.—The 3.1 μm equivalent width is plotted as a function of the $K-L$ color. The lines are least-squares fits for the LMC sample (*solid line*) and the Galactic sample (*dashed line*).

4. CHEMICAL EQUILIBRIUM MODELS

For lower elemental abundances, the molecular abundances will also be affected by the lack of metals (e.g., seen in Fig. 4 of Marigo 2002). The equivalent widths of molecular bands are thus expected to be smaller in the LMC.

To quantify this, we calculate chemical models for the stellar atmospheres. We assume local thermodynamic equilibrium to compute the relative molecular abundances (Markwick 2000), for a range of temperatures and metallicities. Figure 5 shows the abundances, in terms of the relative partial pressure, for HCN and C_2H_2. [Z/H] = 0.0 and −0.3 represent the solar and LMC metallicities, respectively. The solar abundances are taken from Anders & Grevesse (1989). Carbon abundances are calculated from the C/O ratio and the oxygen abundance. In the [Z/H] = −0.3 model, all elemental abundances are half of the solar abundance ([Z/H] = 0.0) except for hydrogen, helium, and carbon. We ignore the metallicity spread among LMC stars.

Figure 5 shows that if the elemental abundance is scaled from the solar abundance, at the same effective temperature ($T_{\rm eff}$) and C/O ratio, the HCN and C_2H_2 abundances at

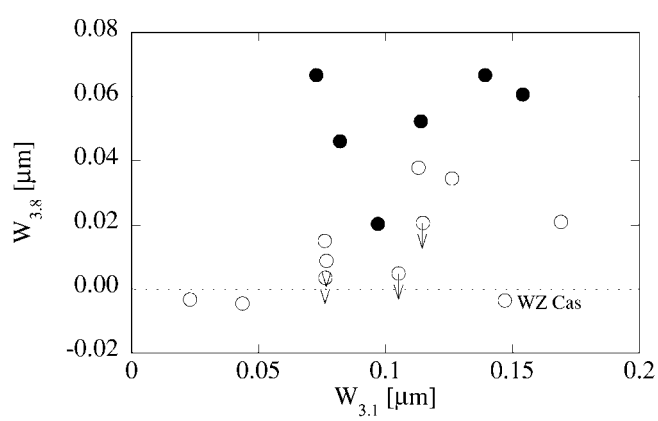

FIG. 4.—The 3.8 μm equivalent width as a function of the 3.1 μm equivalent width. 3.8 μm nondetected stars are marked with an arrow if they have a positive value of $W_{3.8}$.

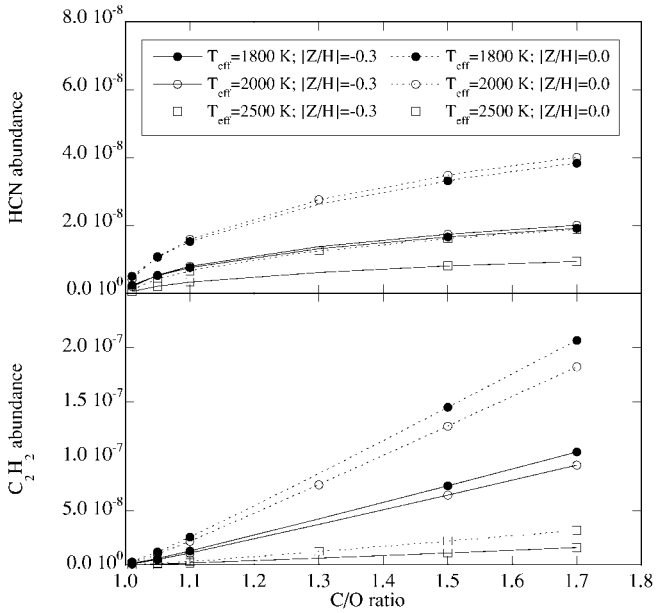

FIG. 5.—Abundances of HCN and C_2H_2 calculated from a chemical model as a function of the C/O ratio. The abundances are partial pressures of molecules divided by the total pressure, which is essentially the same in all models, and are equivalent to column densities. [Z/H] = 0.0 and −0.3 represent the solar and LMC metallicities, respectively.

[Z/H] = −0.3 are predicted to be approximately half of those at the solar abundance. Our observations are inconsistent with this.

However, Figure 5 suggests that our observations can be explained if the C/O ratio is systematically higher in LMC carbon stars. The HCN and C_2H_2 abundances increase with increasing C/O ratio. The C/O ratio in the Galactic carbon stars is about 1.05–1.1 on average (Lambert et al. 1986; Ohnaka, Tsuji, & Aoki 2000). Our observations then suggest that LMC carbon stars have a C/O ratio more than 1.2, if we assume that the effective temperature of the stars and the excitation temperature of the molecular bands are the same as for the Galactic carbon stars.

Elemental abundances in planetary nebulae, which are the end products of AGB evolution, also suggest a high C/O in the LMC (Leisy & Dennefeld 1996). Therefore, it is reasonable to conclude that the C/O ratio is systematically larger in the LMC.

In Figure 5, the HCN abundance increases slowly at higher C/O ratio, while C_2H_2 increases linearly. C_2H_2 is more sensitive to the C/O ratio. This could explain our finding that the metallicity dependence is stronger at 3.8 μm (C_2H_2) than at 3.1 μm (HCN + C_2H_2).

In general, stars are oxygen-rich when they enter the AGB phase. Third dredge-up leads to ^{12}C enrichment in the atmospheres of AGB stars. If the C/O ratio exceeds unity after the third dredge-up, the star is classified as a carbon star. Theoretical models have predicted that the amount of ^{12}C enrichment through the third dredge-up increases with lower metallicity (e.g., Vassiliadis & Wood 1993). This explains why the number ratios of oxygen-rich and carbon stars are different in the solar neighborhood, Galactic bulge, and the Magellanic Clouds. Evolutionary models of stars with initial masses greater than 2.5 $M_\odot$ by Vassiliadis & Wood (1993) show that at the LMC metallicity, the ^{12}C abundance increased by a factor of 2 at the end of the thermal pulsing AGB phase, relative to the abundance after the second dredge-up, while the ^{16}O abundance remains almost constant. On the other hand, the ^{12}C abundance increased only by 50% at solar metallicity. Therefore, their models predict that the C/O ratio is in general higher in LMC AGB stars than in Galactic AGB stars. Our observations agree with this prediction.

In conclusion, the elemental abundances of LMC carbon stars extrapolated from the simple scaling from the Galactic carbon stars are not appropriate to explain the infrared spectra of carbon stars in the LMC. As pointed out by Marigo (2002), the enrichment of elements in the atmosphere through the third dredge-up should be also considered.

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REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Aoki, W., Tsuji, T., & Ohnaka, K. 1998, A&A, 340, 222
Gezari, D. Y., Schmitz, M. M., & Jaylee, M. 1993, Catalog of Infrared Observations (Greenbelt: NASA GSFC)
Goebel, J. H., Bregman, J. D., Witteborn, F. C., Taylor, B. J., & Willner, S. P. 1981, ApJ, 246, 455
Groenewegen, M. A. T., de Jong, T., & Geballe, T. R. 1994, A&A, 287, 163
Hron, J., Loidl, R., Höfner, S., Jørgensen, U. G., Aringer, B., & Kerschbaum, F. 1998, A&A, 335, L69
Lambert, D. L., Gustafsson, B., Eriksson, K., & Hinkle, K. H. 1986, ApJS, 62, 373
Lançon A., & Wood P. R. 2000, A&AS, 146, 217
Le Bertre, T. 1992, A&AS, 94, 377
Leisy, P., & Dennefeld, M. 1996, A&AS, 116, 95
Loidl, R., Aringer, B., Hron, J., Kerschbaum, F., Höfner, S., Jørgensen, U. G., & Windsteig, W. 1999a, in The Universe as Seen by *ISO* (ESA SP-427; Noordwijk: ESA), 365
Loidl, R., Höfner, S., Jørgensen, U. G., & Aringer, B. 1999b, A&A, 342, 531
Marigo, P. 2002, A&A, 387, 507
Marigo, P., & Girardi, L. 2001, A&A, 377, 132
Markwick, A. J. 2000, Ph.D. thesis, UMIST
Noguchi, K., Kawara, K., Kobayashi, Y., Okuda, H., Sato, S., & Oishi, M. 1981, PASJ, 33, 373
Ohnaka, K., Tsuji, T., & Aoki, W. 2000, A&A, 353, 528
Péquignot, D., Walsh, J. R., Zijlstra, A. A., & Dudziak, G. 2000, A&A, 361, L1
Trams, N. R., et al. 1999a, A&A, 346, 843
———. 1999b, A&A, 344, L17
van Loon, J. Th. 2000, A&A, 354, 125
van Loon, J. Th., Zijlstra, A. A., & Groenewegen, M. A. T. 1999, A&A, 346, 805
Vassiliadis, E., & Wood, P. R. 1993, A&A, 413, 641
Yamamura, I., de Jong, T., Justtanont, K., Cami J., & Waters, L. B. F. M. 1997, Ap&SS, 255, 351